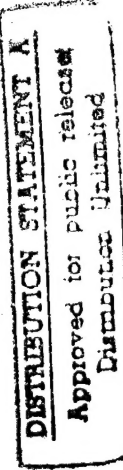


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## Blue Cesium Faraday and Voigt Filters

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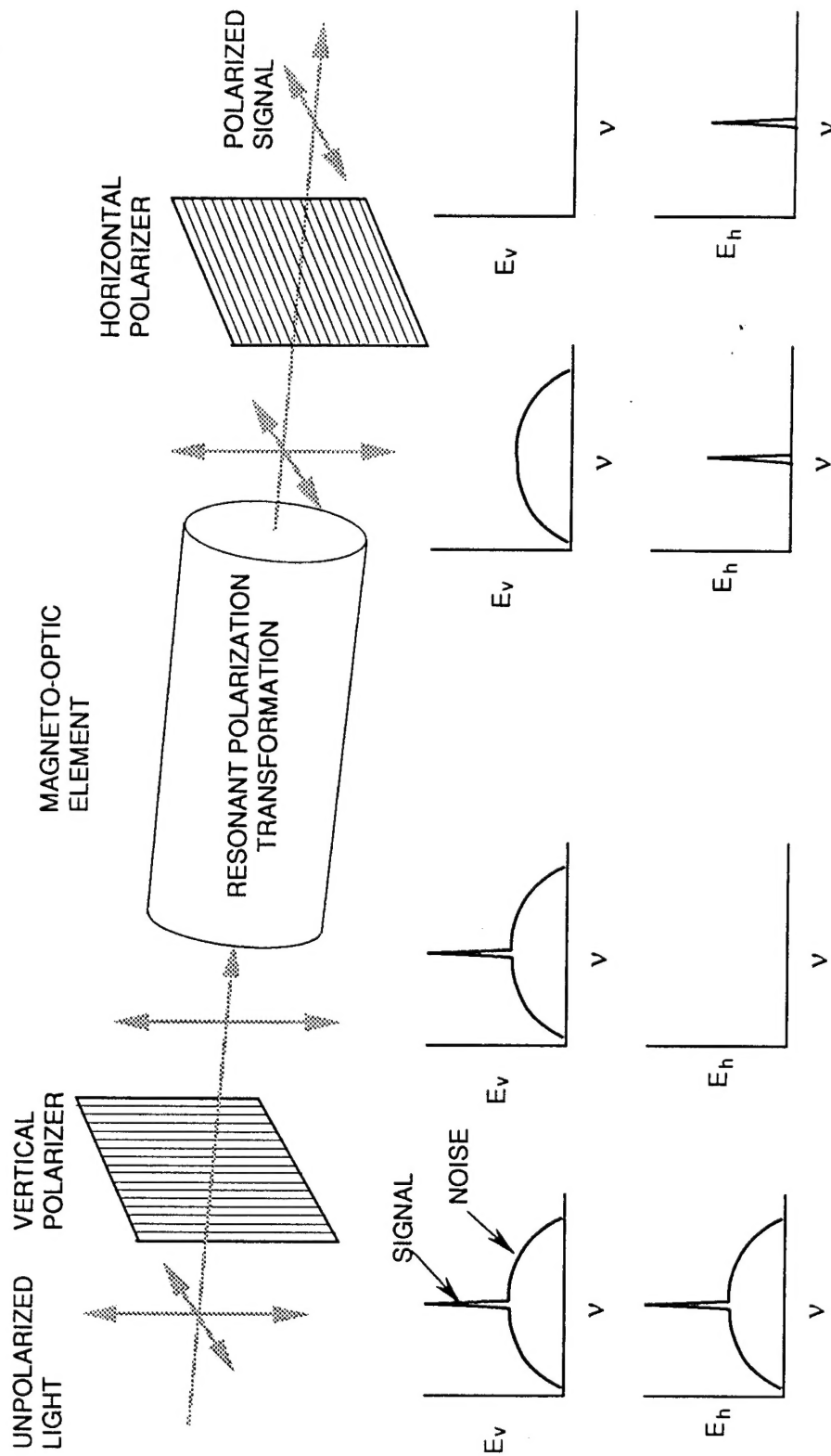
## ULTRA-NARROW MAGNETO-OPTIC ATOMIC LINE FILTERS FOR LASER RECEIVERS

- Background limited laser receivers require ultra-narrow linewidth filters to reach quantum limited operation
  - submarine laser communication
  - free space communication
  - remote sensing
- Like the conventional absorptive/re-emissive atomic line filters (ALF), the M-0 ALFs
  - operate at discrete atomic absorption lines
  - have Doppler limited passbands
- However, M-0 ALFs are imaging filters with
  - very high peak transmission
  - wide field-of-view
  - instantaneous response

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- Principles of resonant magneto-optic filter operation
- Modelling approach to magneto-optic filters
- The Faraday and Voigt filters
- Setup for spectrum measurements
- Faraday filter spectra - measured and calculated
- Voigt filter spectra - measured and calculated
- Off axis transmission measurements and predictions at 455 nm
- The Faraday filter field-of-view

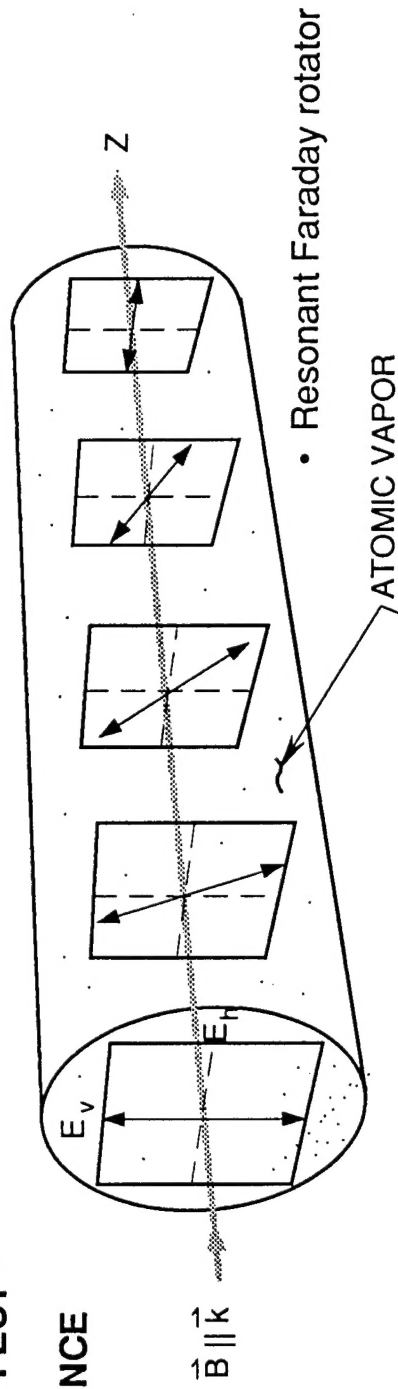
## PRINCIPLES OF RESONANT MAGNETO-OPTIC FILTER OPERATION



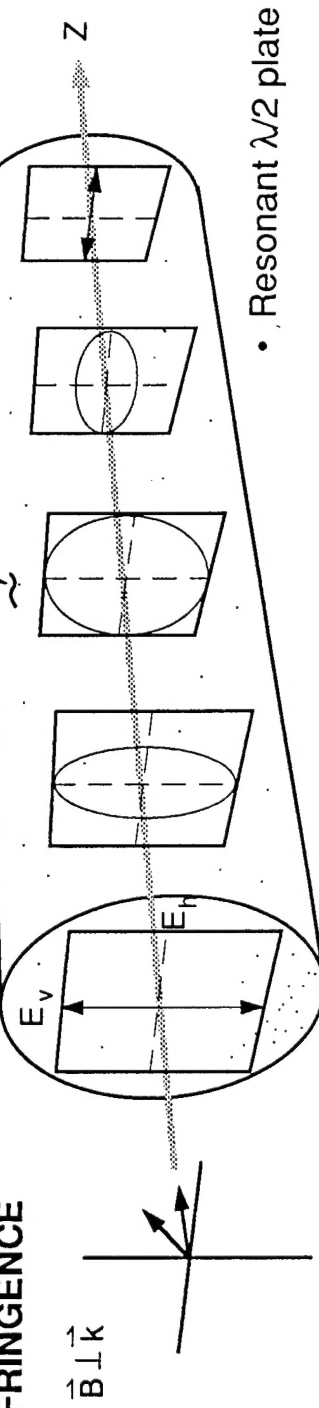
- The magneto-optic element transforms vertical into horizontal polarization over a narrow spectral band
- In-band light is transmitted; out-of-band light is blocked

## FARADAY AND VOIGT EFFECTS IN ATOMIC VAPORS PROVIDE RESONANT MAGNETO-OPTIC ELEMENTS

### FARADAY EFFECT - CIRCULAR BIREFRINGENCE



### VOIGT EFFECT - LINEAR BIREFRINGENCE



### Atoms in a Magnetic Field

- Cs,  $6^2S_{1/2} \rightarrow 7^2P_{3/2}$ ,  $\lambda = 455 \text{ nm}$
- $H' = (\text{hyperfine} \sim \vec{I} \cdot \vec{J}) + (\text{Zeeman} \sim \vec{B} \cdot \vec{J})$
- $E_{\text{FMF}}(B)$ ,  $| \text{FMF} \rangle$
- $P_{ij}(\sigma_+)$ ,  $P_{ij}(\sigma_-)$ ,  $P_{ij}(\pi)$

### Vapor Optical Coefficients

- $N(T)$ ,  $g_D(\nu)$
- $\alpha(\sigma_+)$ ,  $\alpha(\sigma_-)$ ,  $\alpha(\pi)$
- $\alpha(\sigma_+)$ ,  $\alpha(\sigma_-)$ ,  $\alpha(\pi)$

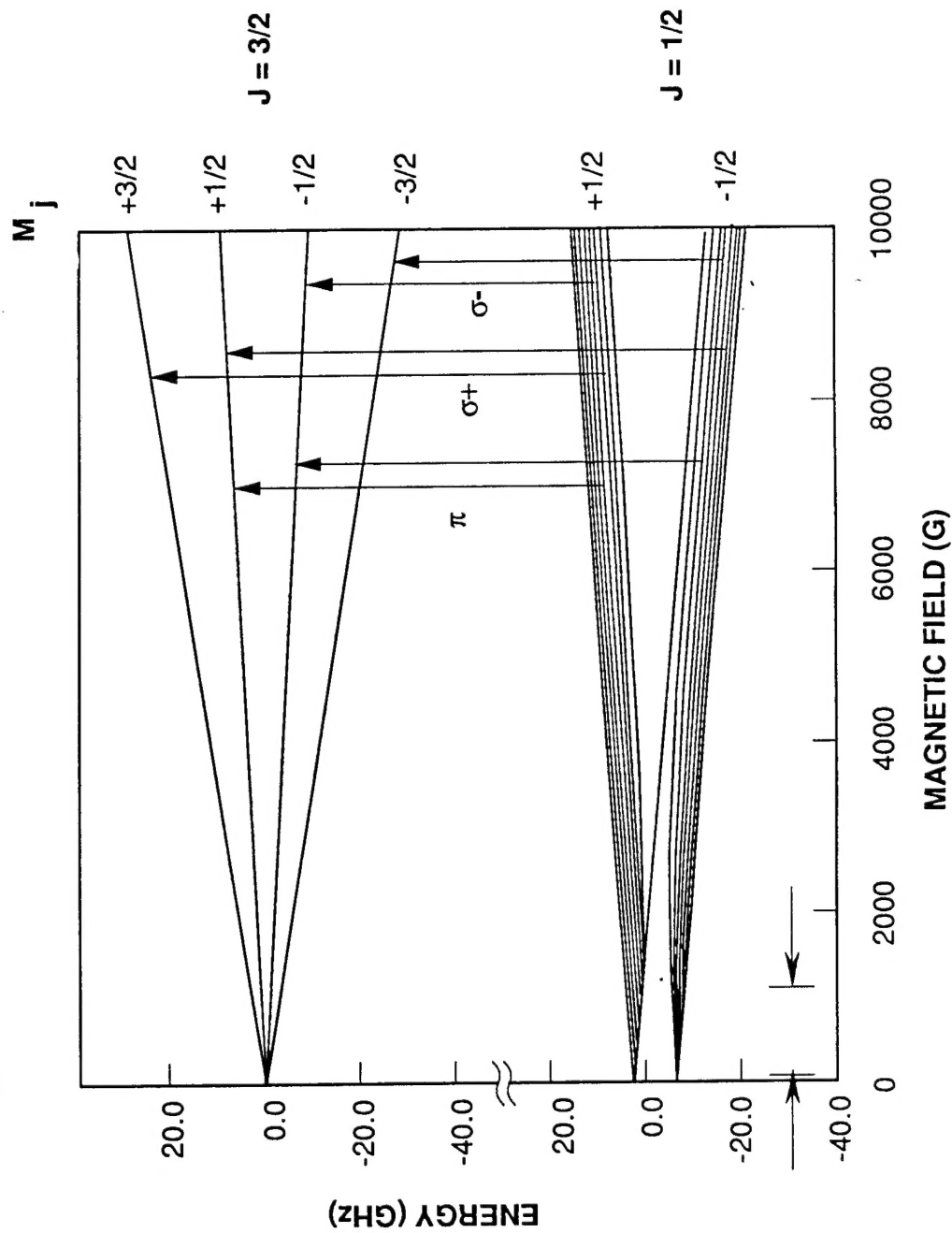
### Propagation Eigen Modes

- $n_i(\vec{k})$ ,  $\vec{e}_i(\vec{k})$

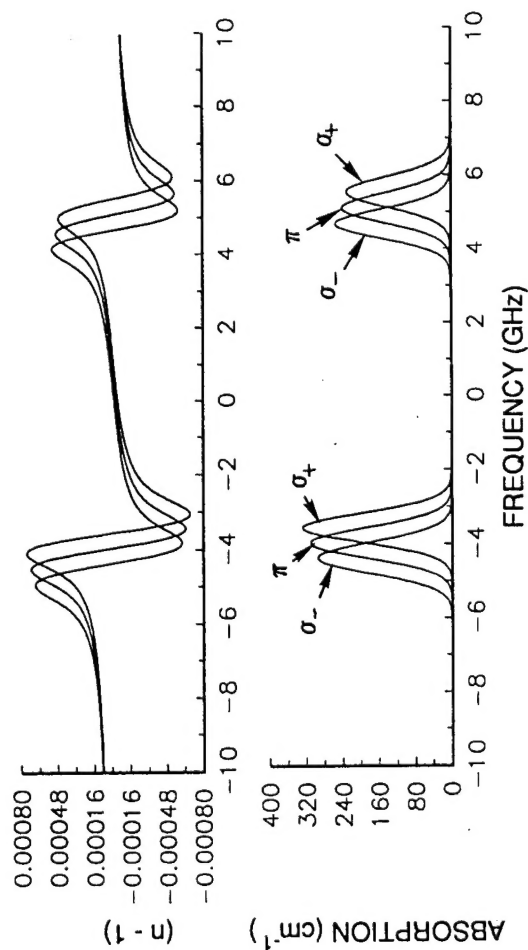
### Transmission Spectrum

- $\vec{E}(z) \sim \hat{e}_1 E_1(o) e^{i(n_1 k_0 z)} + \hat{e}_2 E_2(o) e^{i(n_2 k_0 z)}$

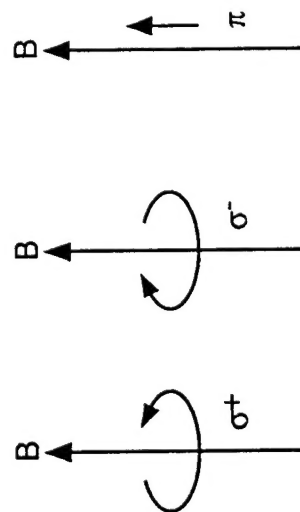
## Cs $6s_{1/2} - 7p_{3/2}$ (455 nm) HYPERFINE AND ZEEMAN SPLITTING



## REFRACTIVE INDICES AND ABSORPTION



Cs, 455 nm  
 T = 200° C  
 B = 200 G  
 L = 1 in.





- In general, other directions have varying eigen-polarizations and -indices
- A simple dielectric tensor w.r.t. the  $\hat{R}, \hat{L}, z$  basis describes the Faraday effect for a field along  $z$

$$\epsilon = \begin{bmatrix} \epsilon_0 & -i\epsilon_B & 0 \\ +i\epsilon_B & \epsilon_0 & 0 \\ 0 & 0 & \epsilon_0 \end{bmatrix}$$

where  $\epsilon_0 = n_L^2$  and  $\epsilon_B = n_F^2 n_L^2$

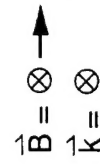
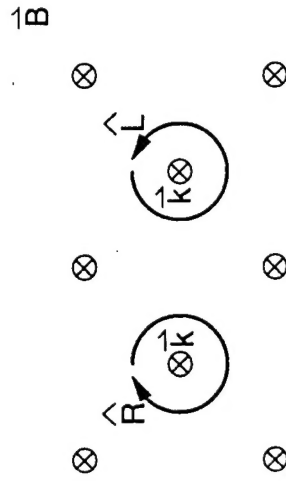
- Maxwell's equations lead to a matrix form of the wave equation

$$\left\{ \epsilon_i \cdot \begin{bmatrix} -s_y^2 - s_z^2 & s_x \cdot s_y & s_x \cdot s_z \\ s_x \cdot s_y & -s_x^2 - s_z^2 & s_y \cdot s_z \\ s_x \cdot s_z & s_y \cdot s_z & -s_x^2 - s_y^2 \end{bmatrix} + [\epsilon] \right\} \vec{E} = 0. \quad \vec{k} = k \hat{s}$$

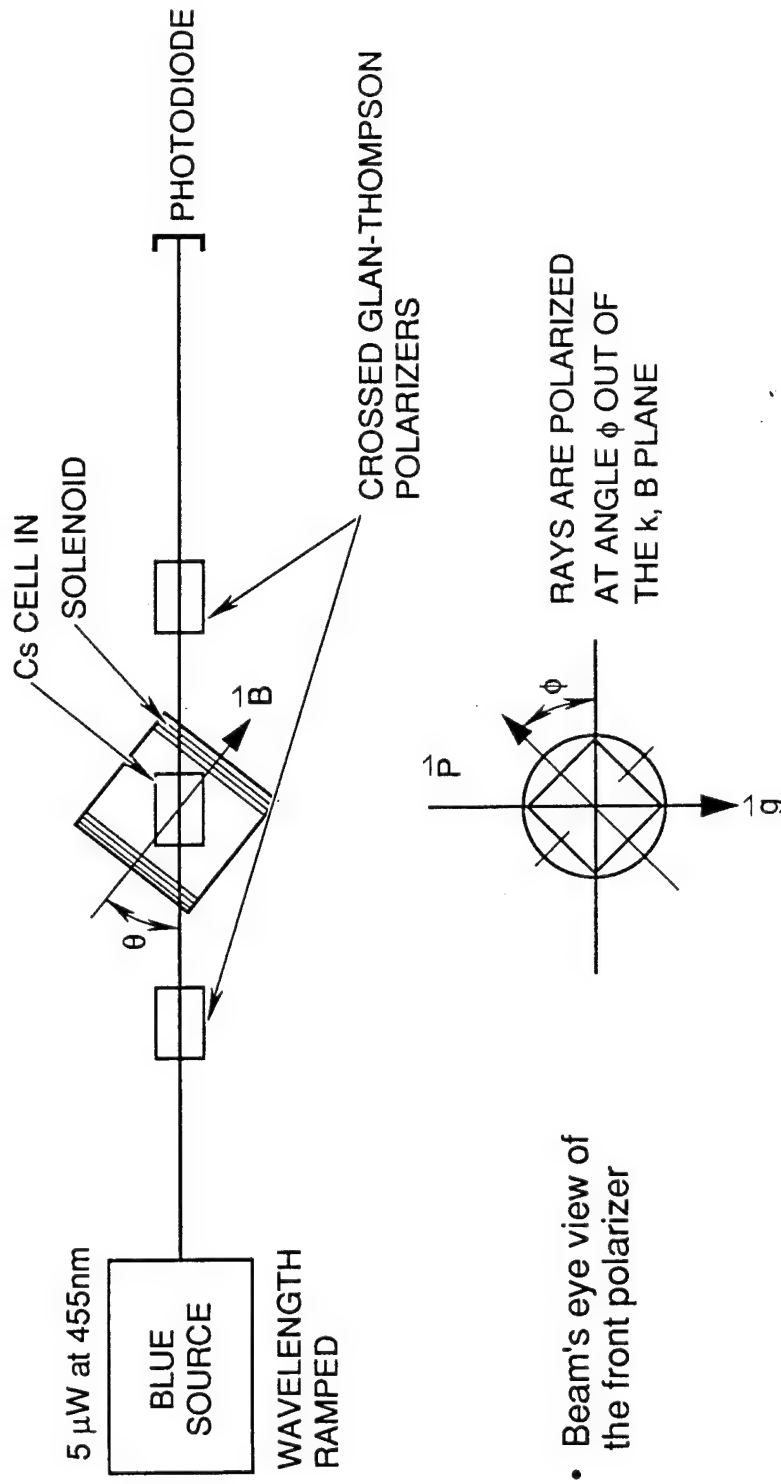
- Eigen - indices  $n_i^2 = \epsilon_i$  are determined from  $|\{...\}| = 0$ .

## TWO PROPAGATION DIRECTIONS YIELD SIMPLE EIGEN INDICES AND POLARIZATIONS

- Propagation along  $\hat{B}$  (Faraday Effect)
  - Circular polarizations  $\hat{R}, \hat{L}$
  - Circular indices  $n_R, n_L$
- Propagation perpendicular to  $\hat{B}$  (Voigt effect)
  - Linear polarizations  $\hat{y}, \hat{z}$
  - $n_y = \frac{1}{2}(n_R + n_L)$ ;  $n_z = n_\pi$
  - Similar to birefringence

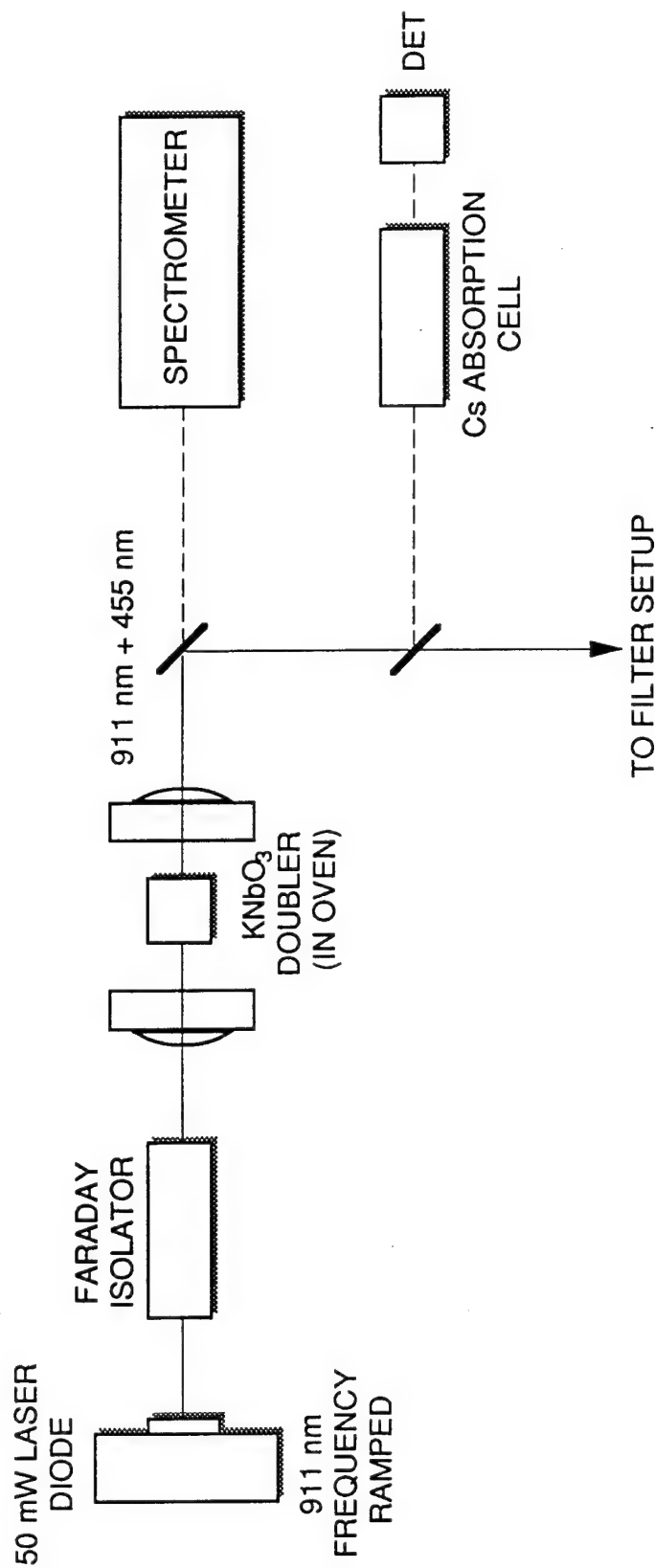


## OFF-AXIS TRANSMISSION EXPERIMENTS



- Beam's eye view of the front polarizer
- This cell and field arrangement avoids the complication of variations in Fresnel losses
- Transmission spectra do not reflect pathlength increases with  $\theta$

# BLUE SOURCE



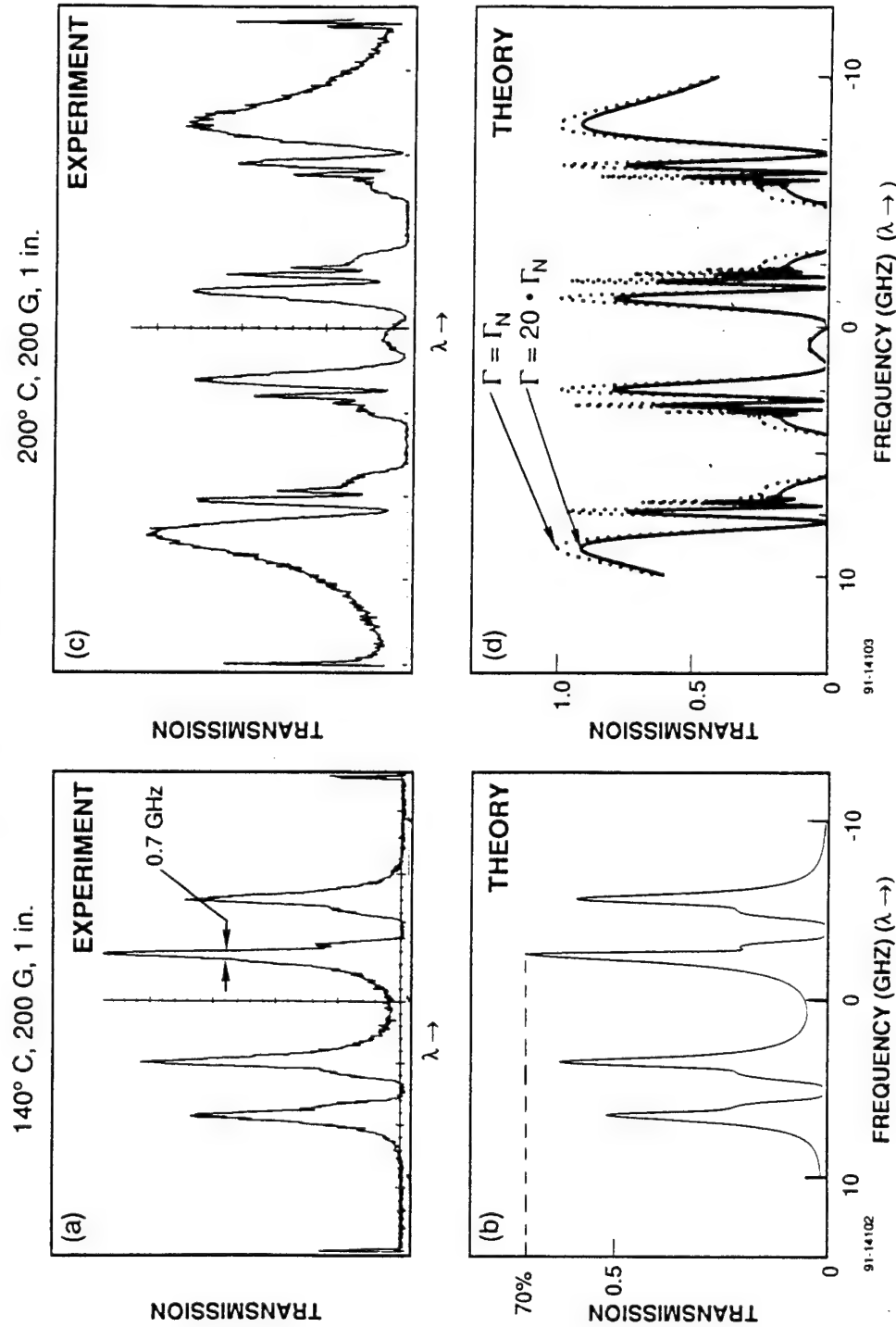
## FILTER TRANSMISSION MEASUREMENT SET-UP

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- The beam and the cell remain fixed
- The solenoid rotates to set  $\theta$
- Crossed polarizers "roll" to set  $\emptyset$

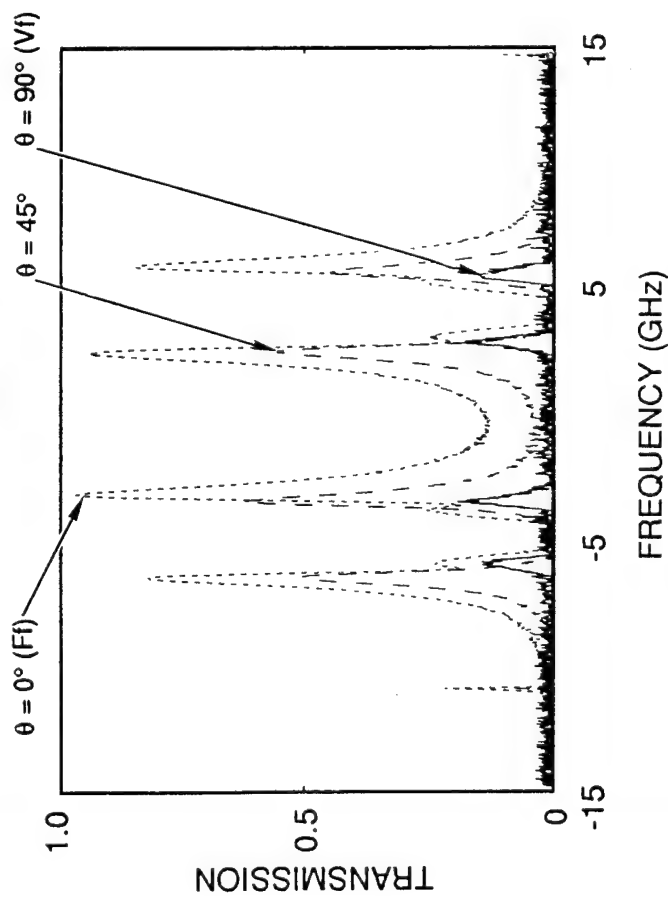
## BLUE FARADAY FILTER ( $\vec{k} \parallel \vec{B}$ ) SPECTRA ARE WELL PREDICTED



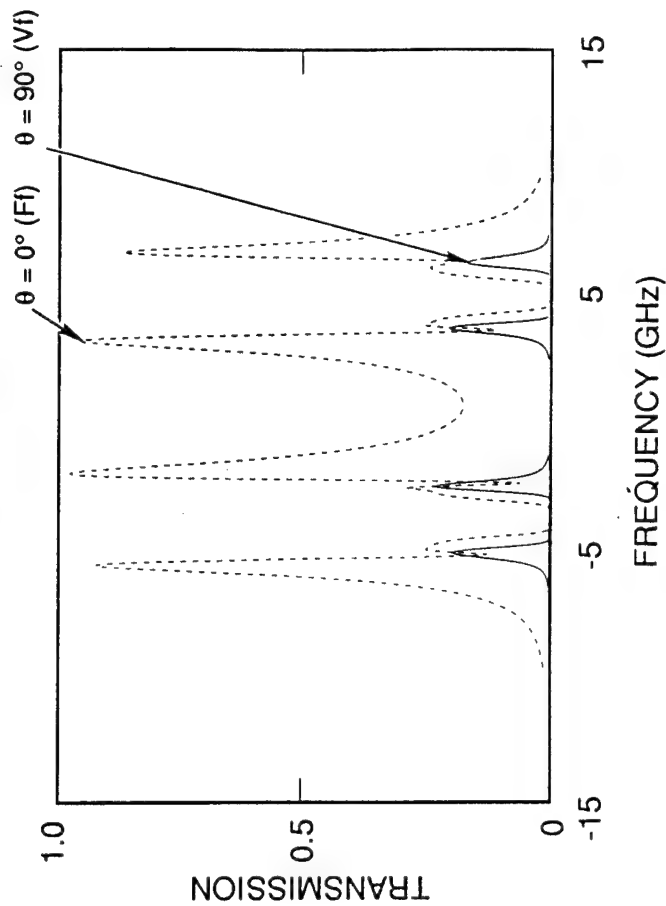
- Optimum conditions minimize bandwidth and maximize transmission
- Additional broadening becomes apparent at temperature  $T \geq 200^\circ \text{C}$

## BLUE FILTER TRANSMISSION vs. $\theta$ AT $\phi = 45^\circ$

### EXPERIMENT

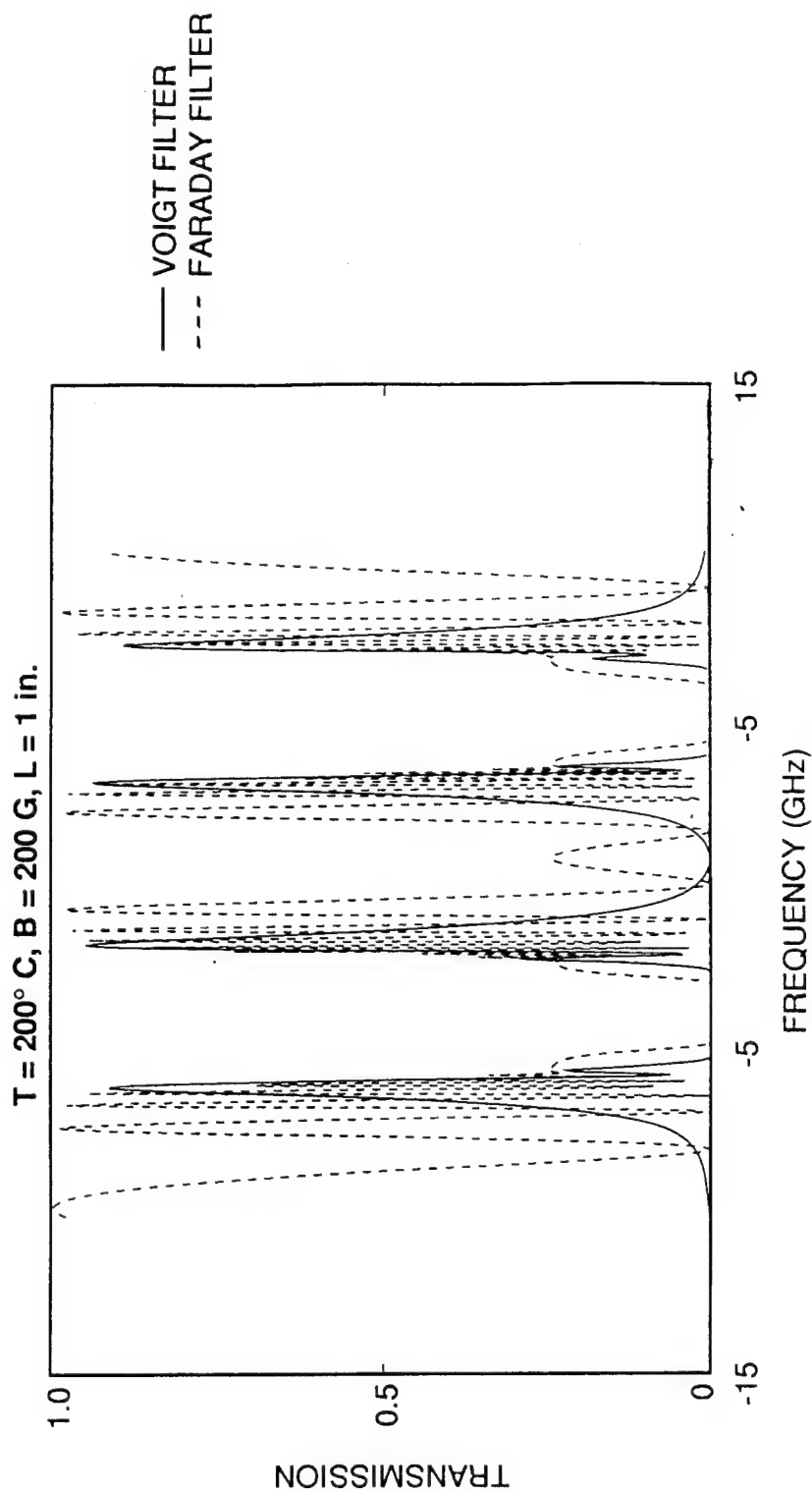


### THEORY



Cs, 455 nm with  $T = 140^\circ$  C,  $B = 200$  G,  $L = 1$  in.

## OPTIMIZED VOIGT FILTER CALCULATION



- High transmission (15%) and narrow bandwidth (0.6 GHz)
- The optimum Voigt filter transmission spectrum occurs at a higher temperature than the optimum Faraday filter spectrum



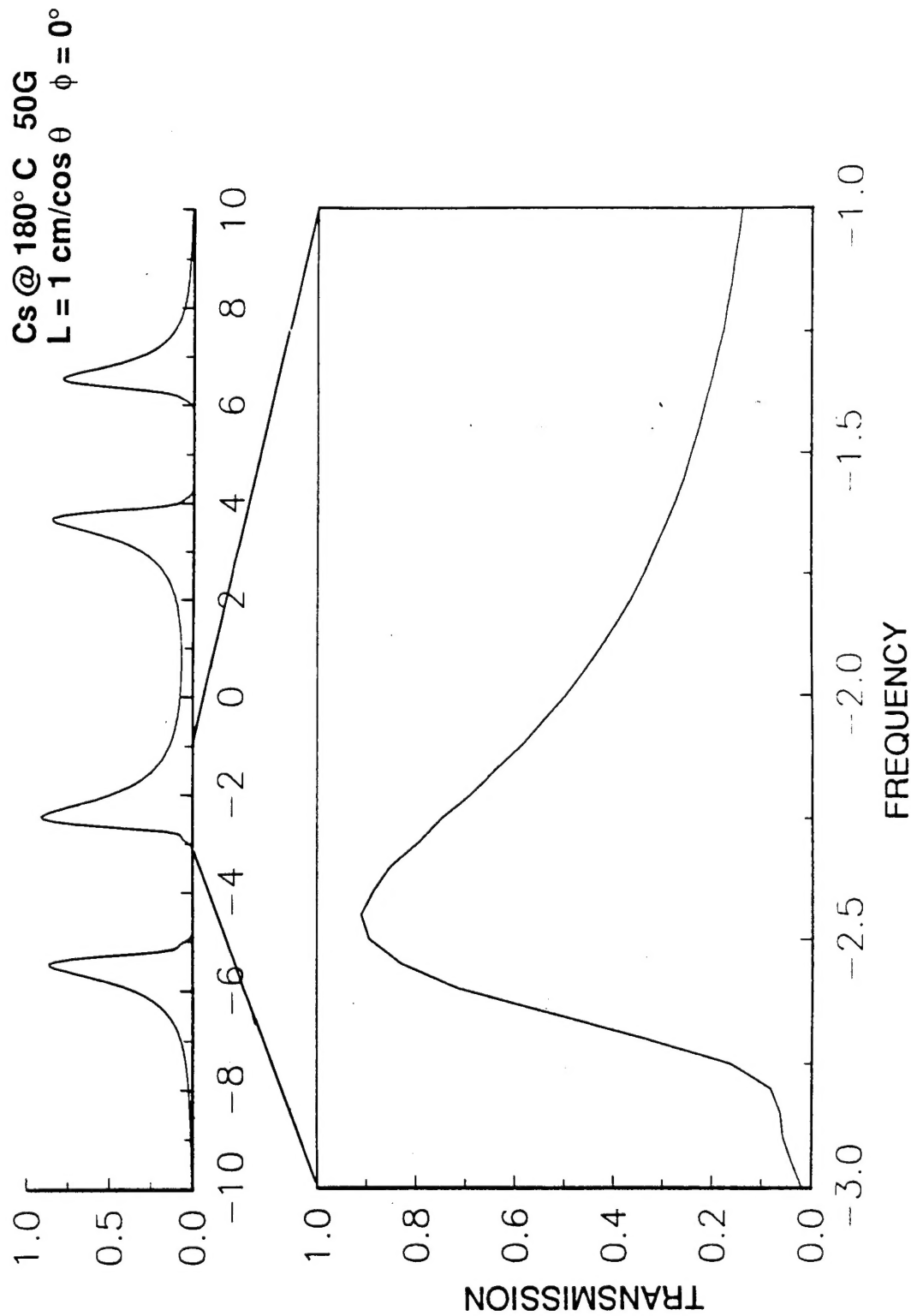
- A heuristic argument led to wide FOV expectations:

$$\text{since } Z = \frac{L}{\cos \theta} \text{ and } \Delta n \propto \vec{B} \cdot \vec{k} = B \cos \theta, \text{ we expect } z \Delta n \sim \text{const}$$

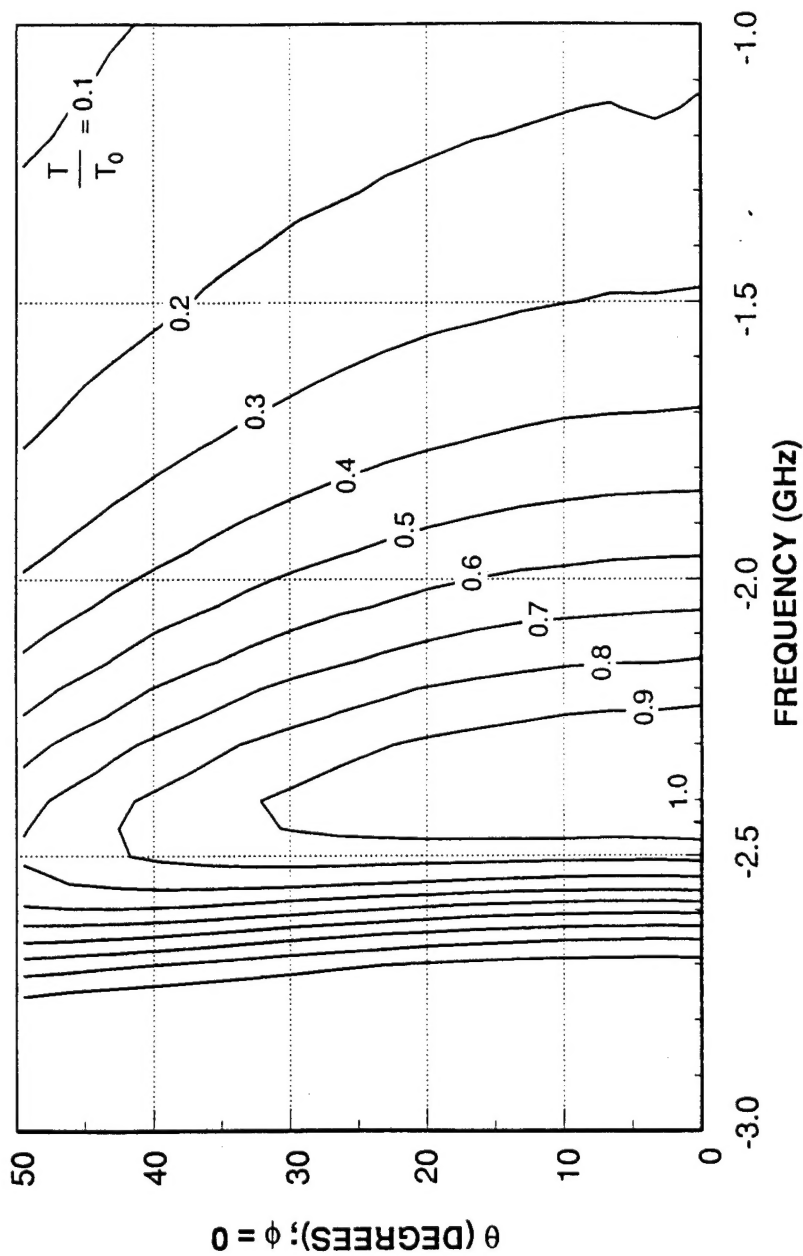
- Approach to FOV assessment
  - Anchor off-axis modelling to experiments
    - z fixed in experiments
  - Calculate FOV ( $z = L/\cos \theta$ )

**TTC**

**WE HAVE ANALYZED THE SENSITIVITY OF A TYPICAL  
BLUE PASSBAND IN DETAIL**



## NORMALIZED TRANSMISSION SPECTRA CONTOURS OVER FIELD ANGLE FOR A PASSBAND NEAR 455 nm



- Faraday filter operated at 180° C, 50 G, 1 cm
- Horizontal slices give spectra at fixed angle
  - Passband position is independent of angle
- Vertical slices give  $T$  vs.  $\theta$ 
  - Peak transmission decreases by 10% for  $\theta = 31^\circ$

## CONCLUSIONS

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- Ultra-narrowband blue Faraday and Voigt filter spectra have been observed
  - Spectra agree with our predictions
  - Near unity transmission
  - ~ 1 GHz passbands
  - 3 GHz integrated transmission
- We predicted and observed a new type of ultra-narrowband filter - the "Voigt filter"
  - Transverse magnet geometries may lead to higher packing densities
- A typical blue Faraday filter passband is insensitive to field angles up to 35°